THIN SILICON-ON-CERAMIC SOLAR CELLS

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ABSTRACT

AstroPower is developing an advanced photovoltaic module product based on thin-silicon on ceramic substrates. This paper reviews the motivations, technical approaches, and electrical results for both single element and monolithically interconnected solar cell devices. Recent results include a 9.1% efficient, 1.0cm^2, single element device and a 5.5% efficient monolithically interconnected four segment, 5.6cm^2, mini-module, both which have been verified by NREL. The monolithically interconnected mini-module had a calculated 7.8% aperture efficiency based on the collecting area of the emitter. Both of these devices utilized a combination of CVD silicon and a ZMR approach.

INTRODUCTION

AstroPower is developing an advanced thin-silicon based, photovoltaic module product. This advanced product requires the following features:

- Silicon layers grown on a low cost ceramic substrate.
- Total silicon layers ≤100µm thick with minority carrier diffusion lengths of the absorber layer exceeding 100µm.
- Light trapping due to back-surface reflection and random texturing.
- Back surface passivation.

These performance design features, combined with the use of low-cost continuous processing equipment, will lead to high performance, low-cost photovoltaic panels. The thin-silicon device structure allows for the use of imperfect materials and increased doping levels, and lowers cost by minimizing the use of expensive feedstock material.

The solar cell device design incorporates light trapping and back surface passivation to improve energy conversion efficiency. Light trapping is achieved by using diffuse reflection from a randomly textured back surface. This results in enhanced optical absorption of weakly absorbed light and improved current generation. Diffusion lengths equal to or greater than twice the device thickness are required to assure efficient carrier collection through the bulk of the base layer. The performance of a thin-silicon solar cell is critically dependent on recombination at the device surfaces, minority carrier diffusion lengths (L_n), and optical losses.

APPROACH

The construction of this thin-silicon device can be broken down to the following functional areas:

1. Ceramic Substrate Development
2. CVD Silicon
3. Silicon Recrystallization
4. Solar Cell Processing

Ceramic Substrate Development

When designing a substrate for the thin-silicon growth, the primary issues that must be addressed are:

- Mechanical stability at growth temperatures.
- Coefficient of thermal expansion (CTE) match to silicon.
- Minimization of impurity diffusion to the active silicon layer.

Structured ceramic substrates that incorporate these properties can be manufactured in a cost-effective manner using a tape casting process. The advantage of tape casting, compared to other ceramic forming processes, such as dry pressing, is that it forms flat pieces with thickness ranges from 25µm to 1250µm. Currently, AstroPower has the capability to cast continuous 12.5 inch wide sheets of ceramic.

Ceramics of varying composition have been formulated, fabricated, and tested by measuring their thermal expansion using a dilatometer. An example of a dilatometer measurement, collected for various ceramic formulations and compared to mC-Si, is shown in Fig. 1.

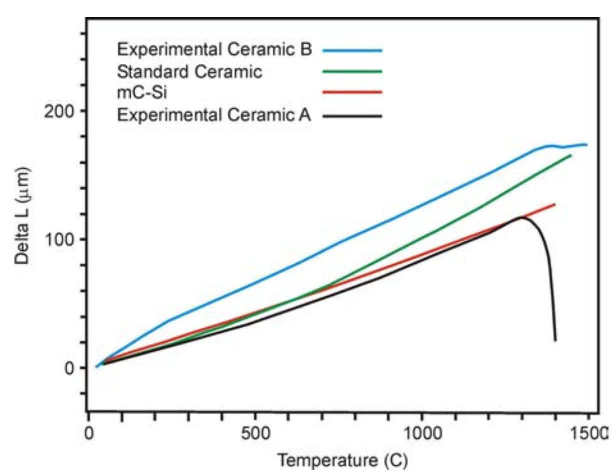

Figure 1. Thermal expansion measurements of various AstroPower ceramics compared to mC-Si.

Experimental ceramic A is almost identical to mC-Si until approximately 1300°C where it begins to melt. This ceramic would therefore not survive the recrystallization process, which would be subsequently performed after the initial polycrystalline Si deposition. Experimental ceramic B attempted to correct this problem, however, as can be seen, the expansion was higher than the standard ceramic. CTE modifiers are continuing to be evaluated as additives to our standard ceramic formulation in order to adjust the CTE closer to that of silicon.

CVD Silicon

Atmospheric pressure CVD silicon was chosen because it has the advantages of good thickness control, high material quality, availability of both epitaxial and polycrystalline growth modes, and high deposition rates. Also, at production levels the cost of silicon in the CVD precursor ranges from $7 to $15/kg, from established industrial suppliers.

The current custom CVD system, shown in Fig. 2, has the following capabilities:

- Large deposition area ($240cm^2$).
- High temperature (>1300°C).
- In-situ HCl etching (1400Å/min).
- Both p and n-type doping (0.02 to 5Ω-cm).
- Fast deposition rates (4-5µm/min).

This system utilizes a high purity quartz processing tube, in-conjunction with a 65kW, 350kHz, RF induction power supply which heats a graphite susceptor. The substrates are heated to deposition temperature by thermal contact with the susceptor. All system components, such as the mass-flow controllers and RF generator, are computer controlled and can be programmed for various deposition “recipes”.

Recent developmental efforts, with respect to CVD, have focused on determining the optimum thickness and doping levels for both the seed and active silicon layers. Both the 9.1% efficient single element and 7.8% aperture efficient monolithically interconnected devices utilized an in-situ HCl etch prior to epitaxy and had the following approximate device structure from top-to-bottom:

- 30-35µm 1Ω-cm p-type epitaxial active layer.
- 10-20µm 0.02Ω-cm p+ in-situ epitaxial back surface field (BSF).
- 50-100µm 0.02Ω-cm p+ recrystallized seed layer.
- 700-800µm non-conductive ceramic substrate.

Continued research towards optimizing these variables is currently underway and will lead to higher conversion efficiencies in the future.

Figure 2. AstroPower custom CVD silicon system.

Silicon Recrystallization

X-ray diffraction (XRD) was performed on a sample of recrystallized silicon-on-ceramic in order to determine the crystallographic orientation, shown in Fig. 3.

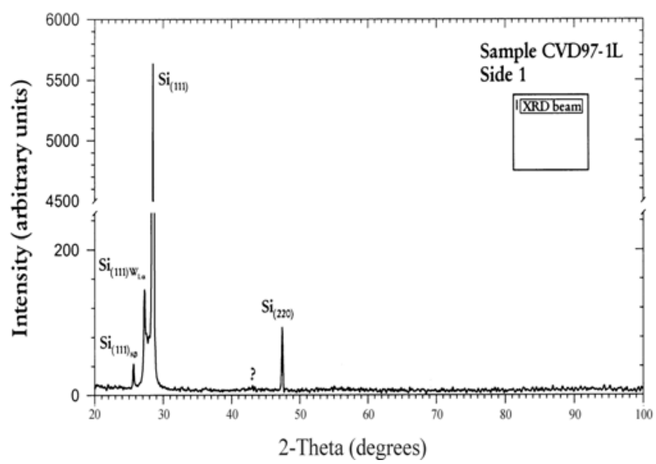

Figure 3. XRD of recrystallized silicon-on-ceramic (Measurements courtesy of Roger Aparicio, Institute of Energy Conversion, University of Delaware).

After testing, the dominant orientation was found to be <111>. This is important to note since a more preferred orientation of <100> is desired after recrystallization. This orientation is believed to lead to a less defect dense silicon layer, e.g. dendritic defects and twinning, and thus a less defect dense epitaxial layer. It has been demonstrated that by varying the scanning speed of the ZMR process, that a majority (90%) preferred <100> orientation can be achieved which has a low defect density ($2x10^6/cm^2$) and excellent electrical properties [3].

A new large area custom light-based ZMR was recently acquired by AstroPower, shown in Fig. 4.

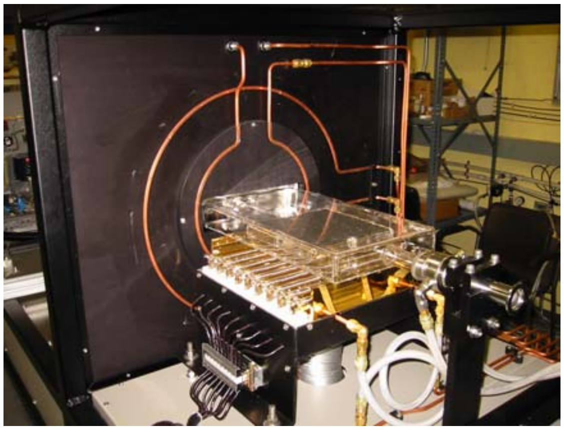

Figure 4. New large area AstroPower recrystallization system.

The primary capability of this system is its ability to recrystallize large areas ($240cm^2$). To accomplish this, the system utilizes a high purity quartz processing tube with a bank of tungsten-halogen bulbs located beneath it. These lights provide up to 54kW of power, which heats the substrate directly, eliminating the need for a susceptor. A single top light (not shown) provides 2kW of power and is used to melt a very narrow band of the silicon as it moves from one end to the other. With this increased power, various scanning speeds will be able to be evaluated and their effect on crystallographic orientation determined.

Solar Cell Processing

Device fabrication of the silicon-on-ceramic structures utilized both laboratory and production scale processes. After epitaxial growth of the BSF and active layer from the recrystallized seed layer, an emitter was formed using a production scale phosphorus-based spray and continuous belt diffusion. The emitter regions of each segment were then protected using photolithography and the samples were plasma etched to isolate the emitter from the base region. Base and emitter contacts were then deposited using photolithography and evaporated metals. At this point the single element device had an anti-reflective coating deposited and was complete. The mini-module, however, must be diced so that each segment has an emitter and base region that are electrically isolated from the other segments. A schematic illustration of the mini-module design is shown in Fig. 5. The dice cuts are made at the top and bottom of the segments, and then between each segment so that the base region (p-contact) to the right of each emitter is included on that segment. The dicing is done so that only the silicon layers are cut but not the ceramic substrate. An anti-reflective coating is then deposited onto the device, and the segments are then electrically connected in series.

The monolithic interconnect process used to connect the four cells in series in the mini-module was performed using an automatic dispensing system. The dispense system, which is capable of depositing 150µm wide lines, is first used to deposit a dielectric epoxy in the dice cuts to provide a shunt barrier. After curing the shunt barrier, a silver containing conductive epoxy is deposited from the emitter of each segment to the base of the adjacent segment to electrically connect the segments in series, and is then cured. Series interconnection is accomplished at the top and bottom of each segment to reduce series resistance associated with lateral current flow. The automatic dispensing process allows us to do away with photo-patterning polyimide as a shunt barrier, and evaporated metals for series interconnection, which was the method previously used in fabrication of the submodule. Other advantages of the automatic dispensing include; ability to dispense after the AR is deposited, resulting in the epoxies not being subjected to temperatures that may cause degradation; no screens or photo-plates required; deposition can be done at speeds of up to 2cm per second depending on the viscosity of the material; and a conveyor can be attached to the system to provide continuous production scale operation. Entire contact metallization schemes have been deposited utilizing the automatic dispense system and work is continuing to optimize the dispense process to allow automatic dispensing of the entire submodule metallization.

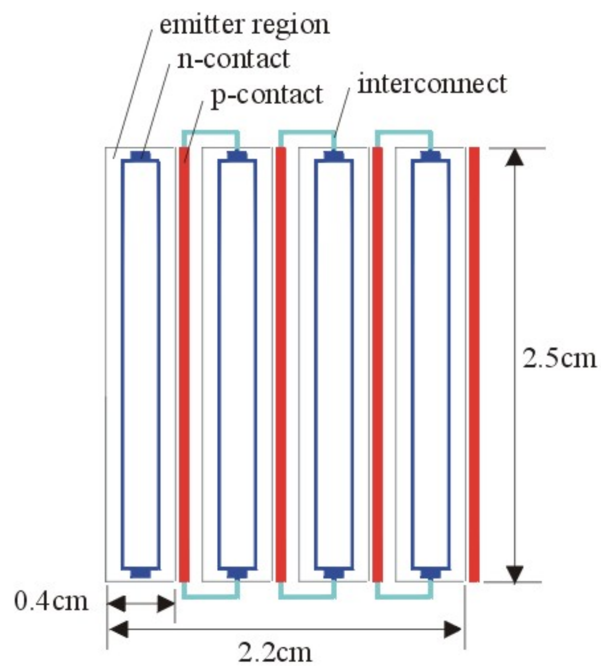

Figure 5. Schematic illustration of mini-module design.

RESULTS

Single Device Efficiency

AstroPower has demonstrated a 9.18% efficient, $1.004cm^2$ silicon-on-ceramic device. The solar cell parameters for this device are: V_{oc} = 0.5430 V, J_{sc} = 23.107 mA/cm^2 and FF = 73.16% (Fig. 6).

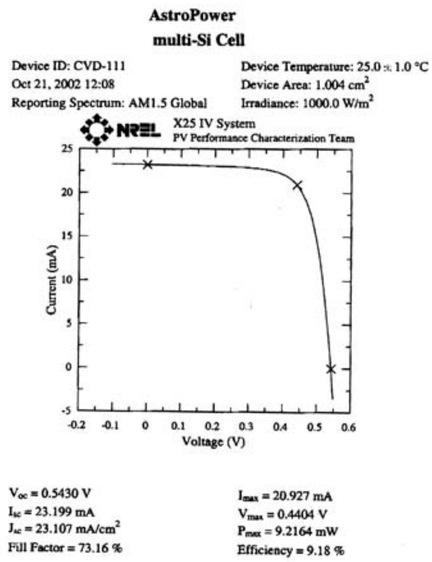

Figure 6. Current-Voltage data for a 9.18% efficient solar cell fabricated using polycrystalline silicon-on-ceramic material.

Monolithically Interconnected Device Efficiency

AstroPower has demonstrated a four-segment 5.55% (7.8% aperture) efficient, 5.641cm^2 monolithically interconnected silicon-on-ceramic mini-module. The solar cell parameters for this device are: V_{oc} = 2.2048, J_{sc} = 3.5206 mA/cm^2 and FF = 71.49%

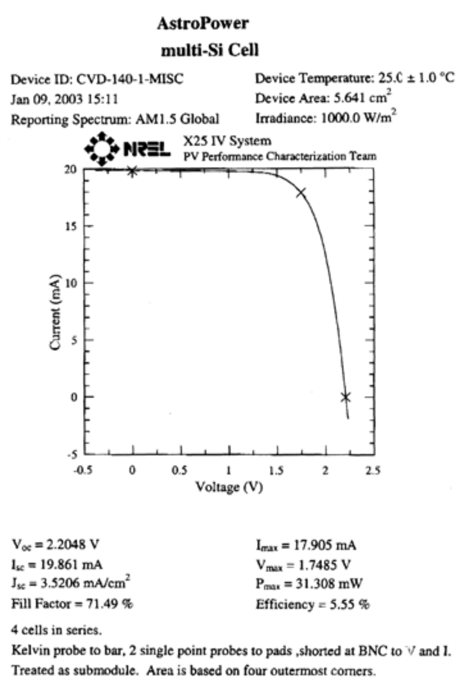

Figure 7. Current-Voltage data for a 5.55% (7.8% aperture) efficient four segment monolithically interconnected solar cell fabricated using polycrystalline silicon-on-ceramic material.

SUMMARY

AstroPower has made significant progress towards the long term-goals of commercialization of a monolithically interconnected solar array product. This work demonstrates the potential of this new class of solar array. Specifically, AstroPower has shown the following:

- Demonstrated a 9.1% efficient single element 1.0cm^2 device utilizing CVD silicon-on-ceramic.
- Demonstrated a 7.8% aperture area efficient four segment monolithically interconnected solar cell utilizing CVD silicon-on-ceramic.
- Acquired a new custom large area recrystallization system.
- Tailored CTE of ceramics over a very broad temperature range.

AKNOWLEDGEMENTS

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REFERENCES

[1] A.W. Blakers, J.H. Wenner, E. Bauser, and H.J. Queisser, *Appl. Phys. Lett*. **60** (1992) pg. 2752.

[2] J.A. Rand, R.B. Hall, A.M. Barnett, Proc. IEEE Photovoltaic Specialist Conference, Orlando, FL, May 1990, pg. 263.

[3] A. Takami, S. Arimoto, H. Morikawa, S. Hamamoto, T.Ishihara, H. Kumabe, T. Murotani, Proceedings 12th EPVSC (114) 59.